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DOCKING AND RETRIEVAL MECHANISM

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ABSTRACT

This paper describes an engineering prototype docking and retrieval mechanism (DRM) which enables two spacecraft to dock and be structurally joined on-orbit. The joining of two spacecraft or payloads on-orbit supports future planned space activities such as payload servicing, deployment and retrieval, and assembly of large space systems. The DRM, as developed,provides advantages over prior approaches because it is a nonimpact docking mechanism, does not require impact absorbing mechanisms or attitude stabilization on the target spacecraft, is capable of docking to a spinning spacecraft, and can spin up and deploy a spinning spacecraft or payload.

INTRODUCTION

The NASA is planning a Space Transportation System (STS) which will possess capabilities and flexibility far beyond that existing today. One of the first steps toward this STS is the Shuttle which is planned to become operational during the latter part of 1970's. The Shuttle will deliver and retrieve payloads and will be able to do a variety of space operations. Typical operations include checkout and deployment of satellites and space probes, servicing of satellites, satellite retrieval, and assembly demonstrations of large space systems.

Within the NASA, special consideration is being placed on the requirement to develop teleoperator technology and space teleoperator systems. The primary goal of this technology is to extend man's capability for doing useful work in a space environment. By allowing man, via teleoperator concepts, to have more control and flexibility over the proposed activities in space, substantial savings in program cost and other important benefits can be realized. Most of the savings occur because new approaches to low-cost payload design, satellite deployment, satellite retrieval, on-orbit experiment procedures, and on-orbit servicing of payloads can be seriously considered.

A teleoperator, as defined by NASA, is a remotely controlled, dexterous, cybernetic, man-machine system designed to enhance and extend man's manipulative, sensory, locomotive, and cognitive capabilities. The distinguishing aspects of a teleoperator are: (1) remote control by man; and (2) being capable of working at a location hazardous, inaccessible, or inconvenient for man.

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The study, from which the DRM evolved, was an effort primarily directed towards the Earth Orbital Teleoperator System (EOTS) (Ref. 1). The EOTS provides a remote maneuverable unit controlled from the Shuttle, the earth, or both. Space applications investigated include on-orbit monitoring and inspection, support of EVA activities, servicing, deploying and retrieving satellites, handling of hazardous materials, assembling large structural systems in space, and overall support of earth orbital payloads.

Recent studies have recommended that a typical EOTS should have the functional capabilities of indirect viewing, remotely controlled maneuverability, rendezvous and docking to other spacecraft, and remote manipulation. The primary emphasis of this paper addresses the docking of the EOTS to other spacecraft and the associated docking hardware development and design.

DOCKING MECHANISM BACKGROUND

Three major space programs which required on-orbit docking have evolved the docking technology most often referenced in establishing future requirements. These include the Apollo, Skylab, and Apollo-Soyuz. The Skylab program continued the use of the Apollo probe and drogue concept, while the latter program used a peripheral type concept.

In summary, the docking concepts evaluated for Apollo were characterized by both impact and nonimpact designs (Ref. 2). The final selection was impact; however, the rationale behind this must be viewed using the requirements that were defined. The advantage of the impact type system is that the kinetic energy of the active vehicle can be transformed into forces to provide the alignment of the two halves of the docking interface. Complications arise because the remaining kinetic energy must be removed through an energy absorption system, typically springs and dampers. It was also noted that, for Apollo, the docking was between two stabilized vehicles. Thus, if the first impact did not effect capture (e.g., Apollo 14), the second attempt was not complicated by the tumbling of one of the vehicles. As the EOTS will be required to dock to passive payloads, the alternative is to provide the EOTS with a control system that enables the desired level of docking alignment and incorporates a nonimpact type docking system. It was also observed that, if the docking concepts can be categorized as either central or peripheral, all the proposed concepts for Apollo were of the central type since there was no requirement for the docking interface to transmit large structural loads. This docking characteristic is similar to the EOTS type of requirements. In addition, most of the docking operational sequences involve two basic activities: (1) aligning and capturing the payload, typically with a set of light latches; and (2) then drawing the two together so that a firm structural connection can be made by a second set of stronger latches.

The EOTS docking mechanism evolution was based on the "lessons learned" from the Apollo program as summarized in "Apollo Experience Report - The Docking System" (Ref. 3). In this report, Robert Langley concludes that one should:

1) Establish realistic design criteria so that simplicity of design can be achieved; remain flexible on arbitrarily established requirements.

2) Integrate the docking system with the initial design of the spacecraft rather than allocate an envelope for "scabbing on" the system at a later date.

3) Design a "forgiving" system by minimizing critical dimensions and sensitive components.

DRM GUIDELINES, ASSUMPTIONS, AND REQUIREMENTS

The review of past docking analyses and studies led to the incorporation of guidelines and assumptions for the EOTS docking mechanism.

These guidelines and assumptions evolved into a preliminary set of requirements as summarized in Table 1. The primary design drivers within this group turned out to be functional performance requirements associated with extend and retract, capture, latch and rotate.

DESIGN CONCEPTS AND ANALYSIS

The preliminary DRM conceptual design unit was separated into two main subassemblies: (1) the extendable mechanism and (2) the continuous rotation capture and latch probe mechanism.

Extendable Mechanism

The extension-retraction requirement baselined was a maximum extension length of 1.8 m (6 ft) with a 0.9 m (3 ft) retraction capability. To satisfy this capability, a three-segment telescoping device was required.

An initial evaluation of different telescoping techniques indicated that a simple sliding tube concept would not work because of the end loading, which causes bending and results in increased binding and friction loads. Therefore, a concept was developed which incorporated roller bearings between the telescopic segments. The next design area investigated was the method for powering the device through its extend and retract cycles. A number of different concepts were analyzed from a very heavy electro-mechanical linear actuator to a lightweight electric bistem unit.

The initial concept selected was a scissor-screw jack-type drive mechanism (see Fig. 1). A lab-type model of the scissor arrangement was built and evaluated. However, it was found that, while this type device would work well when under a continuous compressive load, it was not suitable for the docking application, which is in tension when docked.

Other approaches were considered (as discussed in Ref. 4) with the ball-screw drive technique (see Fig. 2) being selected as the best.

Probe Mechanism

A review of the various probe mechanism concepts developed during the EOTS docking device analysis led to the selection of a baseline probe. The guidelines used were: (1) minimize the probe diameter to maximize the relative probe-to-adapter ±5 cm (2 in.) radial misalignment requirement, and (2) provide continuous rotation of the latch mechanism without the use of electrical commutation across the rotating joint.

Numerous latch methods, ranging from complex to simple (Ref. 4), were evaluated. The approach selected was one in which the latches are initially deployed to effect capture and then drawn rearward an amount equal to the required longitudinal misalignment of approximately 10 cm (4 in.). A drawing of the probe assembly is shown in Figure 3.

DRM UNIT BUILD

The preliminary set of engineering drawings were delivered to the model shop for estimates on fabrication and assembly costs. The resulting cost estimate was greater than the funds available. A design review was initiated at this time to see if costs could be reduced to a level more in line with the initial proposal estimate. The areas addressed first included those subsystems having the greatest cost discrepancy. The greatest cost discrepancy was traced to the extendable assembly unit. Furthermore, the high cost elements were screened down to two primary subassemblies: (1) the machining and assembly of the hardened steel ball race assemblies mounted between the telescopic segments, and (2) the machining and welding of the triangular telescopic sections (Fig. 2).

Different solutions to reducing these high-cost problem items were investigated. The result of this investigation was a cost reduction plan using a step approach ranging from a major redesign to a minimal redesign. The initial step in the major redesign was to investigate the feasibility of using off-the-shelf hardware.

Therefore, several vendors of extendable devices were contacted. A pair of mechanisms were procured, evaluated, and found acceptable for incorporation into the DRM design. The design was then modified (see Fig. 4) to incorporate the off-the-shelf extendable mechanism. Part of this modification included replacement of the outer triangular section with a commercial cylindrical tube. An inherent design feature of the extendable mechanism allowed for the elimination of the middle triangular section. With these major modifications incorporated into the design, fabrication and assembly costs were reduced significantly to a level more in-line with the initial proposal cost estimate.

Fabrication and assembly of the unit proceeded smoothly with only minor problems being encountered due to fit and slip checks associated with some of the tight tolerances.

DRM OPERATION

The prototype DRM design requirements and drawings which make up the extendable assembly, the probe assembly, and the docking receptacle are contained in Reference 4. With reference also to Figure 5, which shows photos illustrating a typical operational sequence: the extendable assembly provides up to a 1.8-m (3-ft) extension and is housed in a 20-cm (8-in.) tubular section. The assembly is actuated by a ball screw drive directly coupled to a dc torquer motor. A brake is mounted near the motor housing to enable holding the extendable assembly in any position without requiring any torquer power. The position of the extendable assembly is provided by a potentiometer attached to the rear of the probe assembly and operating off a small gear rack.

The probe assembly consists of a forward capture/latch mechnism and a spin-despin drive. The forward capture/latch mechanism incorporates three latching prongs attached to a traveling carriage. The latch drive unit (located to the rear of the spin-despin drive unit) consists of a dc torquer motor, a brake, a potentiometer, and a ball screw assembly. The motor rotates the ball nut which moves the ball-screw forward and backward. This action results in the translation of the forward capture latch mechnism. As illustrated in the photo sequence, during the initial portion of travel, the latches are deployed to an angle of approximately 45 degrees. Subsequent travel results in translation of the fully deployed latches rearward drawing the docking receptacle on the spacecraft and an interface ring on the probe into contact, resulting in a rigid mating. The position of the latch mechanism is indicated by a potentiometer riding on a gear rack. The brake provides the ability to permit the full latching force to be in effect without requiring any motor power.

The spin-despin drive unit consists of a motor and a tachometer. The motor rotates the complete forward portion of the docking probe including the capture latch mechanism. The tachometer provides an output proportional to the probe spin rate up to 100 rpm. In addition to providing the satellite spin-despin capability, this drive is also used for relative positioning of the two spacecraft once docking is effected. A probe spin-lock, mounted on the extreme forward portion of the 20-cm (8-in.) tube, has six locking guides at 60 degree increments. Through use of the spin drive, any one of the locking guides can be selected which will change the relative position between the two spacecraft. This is a requirement for satellite servicing missions and eliminates the necessity of more than one docking maneuver.

The docking receptacle shown is that portion of the DRM assembly mounted on satellites to provide a docking interface for the DRM probe-extension assemblies. The receptacle consists of a flat plate with a centrally located hole which accommodates insertion of the probe. The receptacle hole diameter is significantly greater than the probe diameter to enable probe insertion, including angular offsets, and space capture without contact.

The DRM assembly weighs: (1) extendable assembly 30.6 kg (67.5 lb), (2) probe assembly 15.0 kg (35.3) lb), (3) probe indexing ring 1.45 kg (3.2 lb), (4) spin lock ring 0.68 kg (1.5 lb) for a total of 48.6 kg (107.5 lb).

DISCUSSIONS AND CONCLUSIONS

The concept developed provided considerable operational flexibility and adequate visual coverage during the different operational sequences. However, the testing period at Martin Marietta was short and allowed only for performance requirement checks from a fixed base.

Additional testing will be initiated by NASA-MSFC to evaluate the docking and retrieval mechanism (DRM) before finalization of the EOTS docking design requirements. This test will be conducted at Huntsville, Alabama in the NASA free-flying mobility unit simulation facility.

The primary areas requiring evaluation are those in which man plays a significant role in its control and operation. These include: (1) EOTS thrust levels/controllability, (2) maneuvering with large c.g. offsets, (3) operation with limited illumination, (4) docking/manipulator/camera boom/module stowage mechanism interactive control, (5) operator workloads/timelines, (6) control and display requirements/layout.

The results of the simulation will provide the preliminary baseline for the EOTS, primarily in all the areas of man-machine control and their interrelationships and interactions.

The design and fabrication of the concept verification DRM resulted in some unique design criteria. The following conclusions can be formulated from these criteria.

1) Designers need to continually be aware of the application of off-the-shelf components and hardware.

2) The probe assembly design enables the transfer of linear motion through a rotating joint without the use of slip ring assemblies to accommodate the electrical wires of the linear motion drive motors. Elimination of the slip ring assemblies results in a simpler design with a reduction in cost and weight. In addition, longer operational life and increased reliability, based on lubrication, wear and failures is available and one source of electromagnetic interference (EMI) is eliminated.

3) The device has an extremely high probability of successful capture on the first attempt without any physical contact between the two spacecraft before capture. One area of interest noted during the

performance verification test was related to angular misalignment during the probe-to-drogue insertion step. Actual angular misalignments of up to ±20 degrees were demonstrated. This is better than the design requirement of ±5 degrees.

4) The constraint that the docking interface on the target vehicle be passive, simple, and lightweight was demonstrated during the performance verification test to be feasible. This could prove to be economically beneficial for future planning.

5) Other possible applications for the DRM are proposed in which the attachment of two objects is desired. One specific application is for use as a satellite docking and retrieval device (i.e., as an end-effector on the Orbiter remote manipulator system). Another application is for use with industrial manipulator system or cargo handling devices. Other applications include ground-based coupler systems (trains, trailers, etc), remotely operated connectors (fluid, electrical), and as a mechanism for use in support of antenna deployment or large space structure assembly.

REFERENCES

1. "Earth Orbital Teleoperator Systems Concepts and Analysis", MCR-76-17 Technical Report, Vol. II, NAS8-31290. Martin Marietta Corporation, Denver, Colorado, May 1976.

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3. Langley, Robert D., "The Apollo Experience Report: The Docking System, JSC, NASA".

4. "Earth Orbital Teleoperator Systems Concepts and Analysis, MCR-76-17 Docking Retrieval Mechanism", Vol. V, NAS8-31290. Martin Marietta Corporation, Denver, Colorado, May 1976.

Table 1 EOTS Docking/Retrieval Mechanism Requirements Summary

FUNCTION	REQUIREMENT	BASIS
• Deliver/retrieve passive three axis stabilized, or spin stabilized, spacecraft.	Spin: ≤ 100 rpm Torque: 2 N-m (1.5 ft-lb)	Section 3.5.9.5 Torque must be less than EOTS thruster capability; time to despin or spinup less than 10 minutes
• Dock under the following conditions:		
Radial Misalignment:	± 5 cm (± 2 in.)	Within manual control capabilities based on man-in-the-loop simulation data (Reference P-34).
Angular Misalignment:	± 5 deg	
Longitudinal Misalignment:	≤ 10 cm (4 in.)	
Angular Rate:	± 0.1 deg/sec	Within the EOTS attitude control capability (Ref. Section 4.2.1).
Lateral Velocity:	0.6 cm/sec (0.02 ft/sec)	
Longitudinal Velocity:	3.0 cm/sec (0.1 ft/sec)	
• Sufficient strength and stiffness to support a spacecraft at all times during the servicing, transport, delivery and retrieval maneuvers.		
Maximum Torques:	Yaw: 200 N-m (150 ft-lb)	Maximum anticipated external torque is 75-ft-lb developed by the manipulator system (i.e., 10 lb at 7.5 ft).
	Pitch: 200 N-m (150 ft-lb) Roll: 200 N-m (150 ft-lb)	
Longitudinal Force:	220 N (50 lb)	Maximum anticipated external source is 10 lb developed by the manipulator system.
• Provide spacecraft capture and latch within the following time constraints		
Capture:	≤ 5 sec	Estimated based on reasonable time constraints
Latch:	≤ 15 sec	
Total:	≈ 20 sec	
• Capable of docking to wide range of payloads		
Maximum payload mass:	12,250 kg (27,000 lb)	Maximum payload mass applicable from the SSPD (Section 3.4).
• Index to reposition, once docked (e.g. relative "roll" relationship between the EOTS and the payload).		
Rotational Rate:	≈ 1 rpm	Enables complete (360 deg) coverage by the manipulator system for servicing activity.
Positional Accuracy:	± 5 deg	Requirements not critical.

Note: The EOTS auto-stabilization mode should be inactivated once the capture and latch phases are initiated; after docking, the auto-stabilization mode may be re-activated.

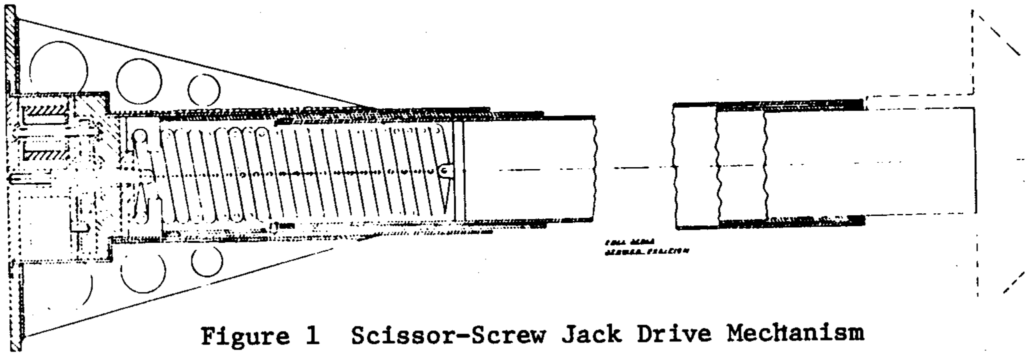


Figure 1 Scissor-Screw Jack Drive Mechanism

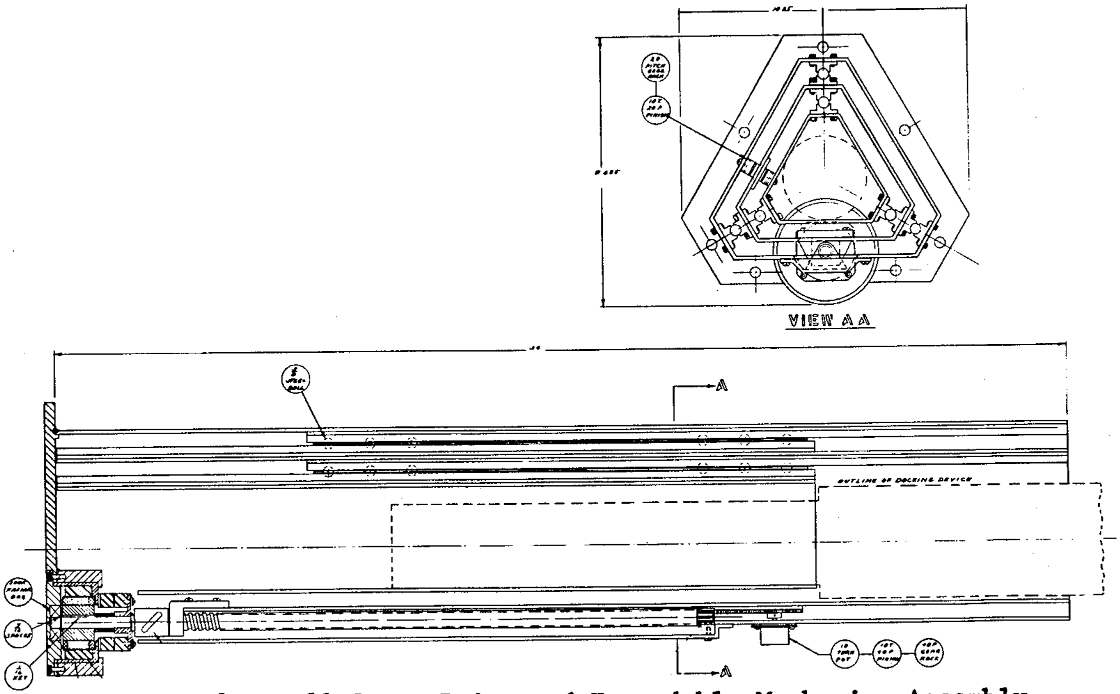


Figure 2   Ball Screw Drive and Extendable Mechanism Assembly

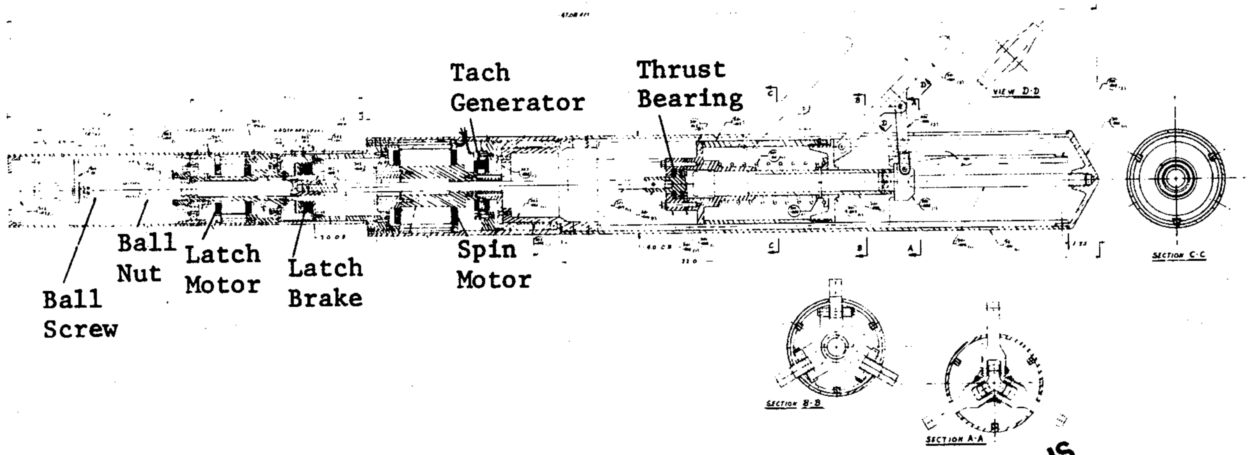


Figure 3 DRM Probe Assembly

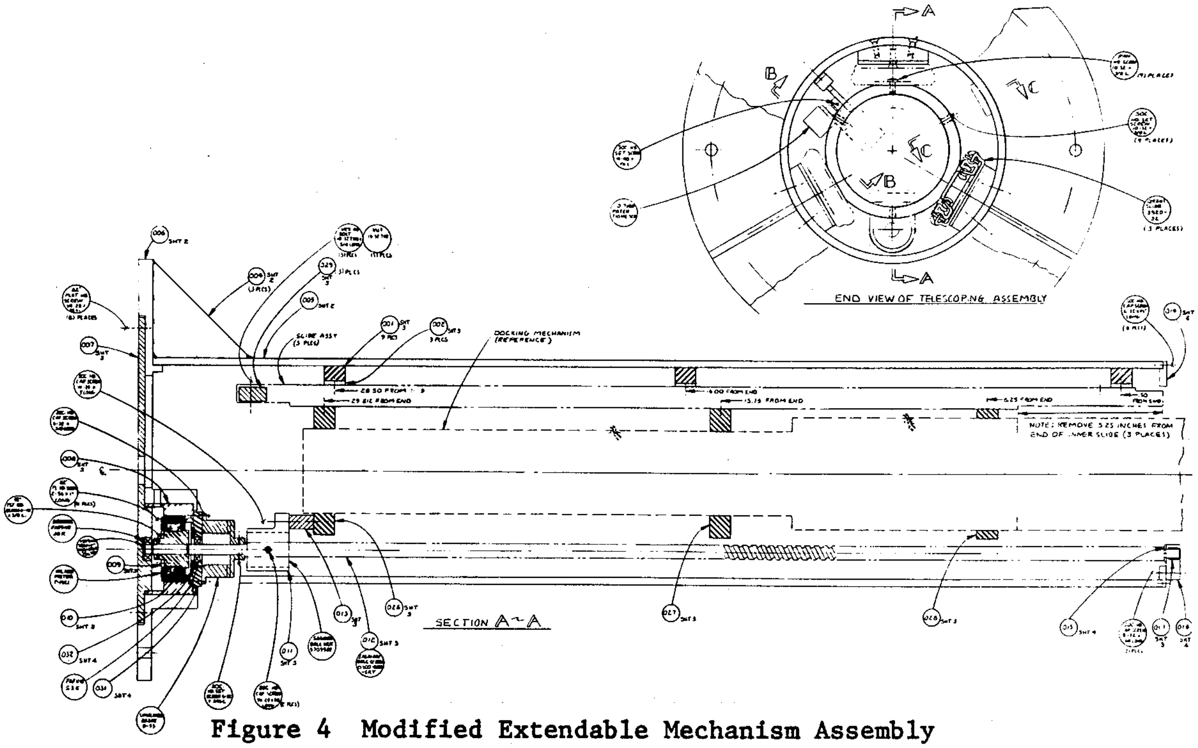
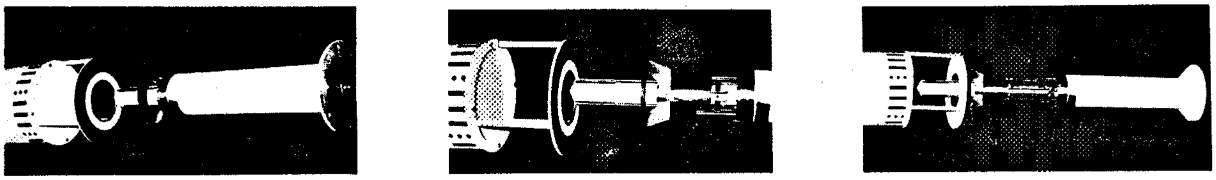
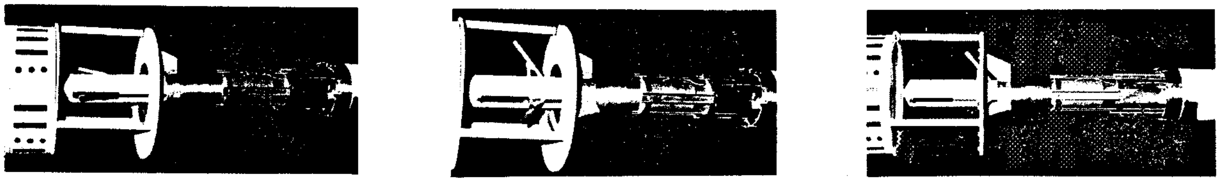


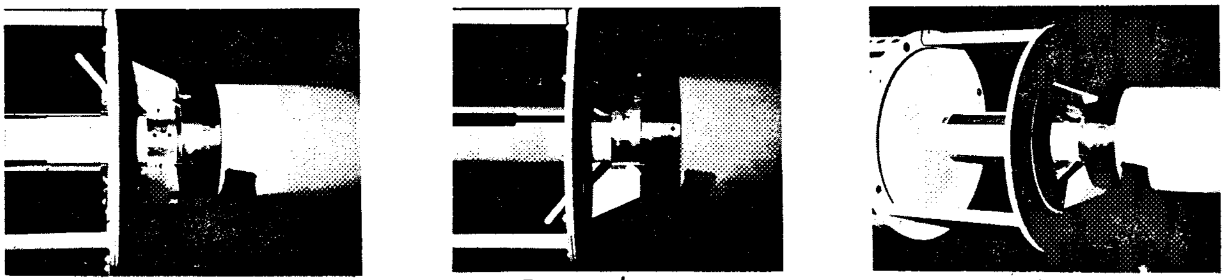
Figure 4 Modified Extendable Mechanism Assembly



Station Keep Extend Insert



Initiate Capture Capture Latch



Retract Rotate/Index Lock

Figure 5 DRM Operation Sequence